Natural degradation of earthworks, trenches, walls and moats, Northern Thailand

Spencer H. Wood[1], Layle R. Wood[2], Alan D. Ziegler[3]

[1]Department of Geosciences, Boise State University, Boise, Idaho, [2]Boise, Idaho, [3]Department of Geography, National University of Singapore, Singapore

We here investigate the geometry, age, and history of several enigmatic northern Thailand earthwork entrenchments that are mostly located on hills and could not have held water to form moats. The earthworks are either oval or rectangular in plan view and typically encircle 0.3 to 1 sq km areas with no potsherd debris that would indicate former towns. Most trenches are 3–5 m deep with inner walls 4.5–8 m high. Some encircling earthworks are concentric double trenches spaced approximately 10 m apart. Historians have suggested these earthworks enclosed defensible areas where people in outlying villages sought refuge when under attack by neighboring rulers, the Chinese Ho, or the Burmese. We argue that some encircling entrenchments may have been for the capture or containment of elephants. Nearly all of the once near-vertical original walls have degraded to slopes of 32–47°. Fitting calculated curves of the diffusion-based scarp-degradation model to our height-slope data, and assuming most scarps have degraded since the end of La Na Kingdom time A.D. 1558, we derive a diffusion coefficient of 0.002 m^2 y^{-1}. Slopes of the rectangular earthwork at Souvannkhomkham, Laos, across the Mekong River from Chiang Saen Noi, are significantly more degraded (approximately 32°), indicating an age of 800–1200 years. Locations of these earthworks are established in hope that they will be preserved as part of the Thai and Lao archaeological legacy.

Keywords: slope degradation, Lan Na Kingdom, Chiang Saen, 14th century, elephants

Introduction

> *"…structures of this kind are hidden away securely under the thick overgrowth: thus does nature preserve what man would surely destroy" (Sumet Jumsai 1970).*

Ruins of brick and stone religious monuments, brick city walls, and earthworks and moats are the enduring relics of northern Thailand's great early kingdoms. This paper focuses on enigmatic earthwork trench systems encircling areas of <1 sq km, some of which are built on hillsides and could not possibly hold water, and therefore are not former moats. The earthworks, originally recognized on aerial photos, are now easily observed on Google Earth images (TABLE 1). Many trench systems do not encircle areas of sherds and brick debris, as would be expected of defensive earthworks encircling ancient towns. The earthwork entrenchments are typically circular—although some are rectangular—and are built across gentle hillslopes, and form enclosures. The entrenchments are typically greater than 3 m deep. Some historians have suggested the earthworks were defensible structures, but we argue below that some may have also had other purposes, such as the capture and containment of elephants. We did not attempt to excavate or date materials of the earthworks in this study, although optically stimulated luminescence dating of excavated materials would establish (at greater expense) a more precise chronology. Instead we analyze the extent of slope degradation on several of these features to better understand the process of slope reduction over time and as a method to estimate their age in the context of Thai history.

Listed in Table 1 are the locations of the earthworks we surveyed, and several unsurveyed locations recently reported to us and confirmed by viewing them on Google Earth. We document the location and characteristics of these features in hope that they will be preserved as sites of interest to tourism and archaeological heritage (cf. Jumsai 1970; Supajanya and Villibhotma 1972).

Historical Background

Earthen walls and moats (i.e., water-filled) encircling larger towns are typical of prehistoric Iron Age (younger than 500 B.C.) and Dvaravati settlements in central and northeastern Thailand (Parry 1992; Boyd

Correspondence to: Spencer H. Wood, Geosciences, Boise State University, Boise, Idaho 83725 USA. Email: swood@boisestate.edu

© Trustees of Boston University 2015
DOI 10.1080/00934690.2015.1103645

Table 1 Locations and dimensions of selected earthwork sites, Northern Thailand

Site name	Latitude	Longitude	Area (sq km)‡	No. of concentric trench-es	Wall height (m)†	Trench depth (m)‡	Maximum slope
Ban Nong Pung (11 km NE of Mae Chan)	20° 12′ 02.12″N	99° 56′ 36.59″E	0.31	1	4.5	3.5	47°
Wat Phrao Chao Lan Thong (3.4 km W of Phrao)	19° 21′ 59.21″N	99° 10′ 08.65″E	(N) 0.13 (S) 0.16	2	7	5	43°
Ban Huai Wiang Wai (2 km E of Mae Chan)	20° 09′ 21.12″N	99° 52′ 46.84″E	(N) 0.33 (M) 0.22 (S) 0.38	1	7.5	4	43°
Wat Phraison Kiri (12 km E of Mae Chan)	20° 09′ 19.87″N	99° 57′ 56.80″E	0.41	2	8	5	42°
Chiang Saen Noi	20° 14′ 31.15″N	100° 06′ 55.74″E	0.68	1	5	4	44°
Chiang Saen city brick wall and earthen moat	20° 17′ 04.22″N	100° 05′ 03.45″E	2.42	1	8.5	4	43°
Souvanna Khom Kham, Laos	20° 15′ 34.50″N	100° 07′ 13.38″E	~1.00	1	3.5	3	32°
Sop Ruak	20° 20′ 30.79″N	100° 06′ 55.74″E	0.42	1	5	1.8	41°
Mae Sai	20° 25′ 17.04″N	99° 52′ 53.08″E	2.37	1	6	6	37° (?)
Thoen*	17° 37′ 46.29″N	99° 13′ 14.01″E	0.10 (?)	2 (?)	*	*	*
Kok River valley, on route 2111 (10 km W of Huai Khian [Highway 1])*	20° 05′ 59.14″N	99° 58′ 10.23″E	(N) 0.006 (S) 0.005	1	*	*	*
Fang*	19° 13′ 52.92″N	99° 13′ 16.27″E	0.20	1	*	*	*
Si Don Mun (6.5 km W of Sop Ruak)*	20 20′ 09.09″N	100 01′ 04.29″E	0.07	2	*	*	*

* site observed on Google Earth but not visited or surveyed
† wall height measured from bottom of trench to top of inner wall
‡ trench depth measured as depth below the original ground surface
(N) = north enclosure, (M) = middle enclosure, (S) = south enclosure

et al. 1999a, 1999b; O'Reilly 2001; Higham 2002; Higham and Thosarat 2012). The Hindu-Buddhist Dvaravati Culture (~A.D. 600–1000) is considered the earliest historical culture in Thailand (Glover 2010). No Dvaravati towns are known in northern Thailand, except Haripunchai at Lamphun, which was founded before the 10th century A.D. (Ongsakul 2005). The only well-studied pre-La Na site is the Iron Age cemetery near Lamphun believed to contain remains from between 500 B.C. and A.D. 200 which are overlaid by a layer with a radiocarbon date from burnt bone of 1490 ± 50 B.P. (CAL A.D. 429–657) (Pautreau *et al.* 2003: 5).

Buddhist monks began writing chronicles as palm-leaf manuscripts in the early 16th century (Penth 1994). Many were written in Pali, translated and recopied many times into archaic Thai script and language. Scholars translating these chronicles into western languages discuss at length problems with authenticity and chronology (Notton 1926; Penth 1994; Wyatt and Wichienkeeo 1998). The chronicle accounts mention towns in the vicinity of present day Chiang Saen and at Mae Sai, both in Chiang Rai Province (Ongsakul 2005: 19–21; Unchaijin 2012). Chronicles of China and Southeast Asia relate legends of early Thai people migrating from southern Yunnan and establishing kingdoms in the area before A.D. 700 (Wyatt 2003; Ongsakul 2005). An early city and kingdom called Wiang Yonok is described in the Sinhanavati Chronicle (Notton 1926) which dates its founding to about the 1st century A.D. (Ongsakul 2005: 19). The Chiang Mai Chronicle relates a history of rulers of the region starting with King Lawacangkarat in A.D. 639, and a succession of 24 rulers ending with the birth of King Mangrai in A.D. 1238, founder of the Lan Na dynasty (Wyatt and Wichienkeeo 1998).

During the Lan Na dynasty (A.D. 1296–1558) many towns were formed with earthen walls; most brick Buddhist monuments and brick city walls were constructed during this time. Hostilities occurred among local rulers, as well as conflict with the Chinese Ho and in the latter part of Lan Na time with the Burmese. The region fell under Burmese rule in A.D. 1558. The various city-states at times asserted their independence and fought the Burmese occupiers. Thai forces finally liberated Chiang Mai from the Burmese in 1775 and Chiang Saen in 1804. Chiang Rai was reestablished in 1844, and the size of the walled town approximately doubled (Penth 2004). Chiang Saen was deserted after defeat of the Burmese, and the old city abandoned. It was found in ruins when visited by the Garnier expedition in the spring of 1867 (Garnier 1885). Le May (1926) saw the city abandoned and covered with vegetation in 1913. Construction of the modern city of Chiang

Saen and restoration of Buddhist monuments has been ongoing since about 1950 (Lertrit 2000).

Previous work on similar earthworks in Southeast Asia

Archaeologists have known about earthworks encircling villages in southeast Asia for many years. The best known are Iron Age moats (i.e., water filled) encircling mounds in the Mun and Chi River basins (FIG. 1) (Boyd *et al.* 1999a, 1999b; Parry 1992; Higham 2012: 186–189) and the Dvaravati-age towns of central and northeast Thailand (Higham 2002: 255–259). Most were fed by streams and had the dual purpose of water management, as well as a defensive structure for a village.

Dega (1999) describes concentric earthen embankments in eastern Cambodia enclosing a 220 m diameter area (1.7 ha), and surrounded by a trench on average 22 m wide and 2.5 m deep, with an outer wall rising an additional 2 meters (i.e., the descent from outside into the trench is ~4.5 m). The earthworks have a wide entryway (>20 m) that is graded down to the outer terrain and the inner platform. Dega (1999) argues that the trenches are not moats, nor do they appear to convey or store water. The enclosed sites contain abundant late Neolithic stone tools and sherds of low-fired, chord-marked, or other incised motif pottery, indicating they were sites of villages. Lack of metal artifacts led Dega (1999) to suggest the sites may be older than 1000 B.C.

According to Ongsakul (2005), northern Thai towns located on river floodplains and surrounded by earthen walls and moats are characteristic of the Hariphunchai Period. Hariphunchai settlements began as northern extensions of the Dvaravati culture of the central plain around A.D. 867. Indigenous Lawa People lived in the surrounding mountains. Both "conch-shaped" and rectangular outlines of towns are found in the southern Chiang Mai basin. Later Hariphunchai towns had a more geometric rectangular form and were surrounded by two earth walls divided by a moat that was used as a reservoir (Ongsakul 2005: 37). Ongsakul (2005: 36) writes that "in the event of an invasion (near a town) people who lived scattered outside the town would gather within its walls."

Chronicles relating the history of the Lan Na dynasty (~1261–1558 A.D.) indicate the initial founding of a typical town involved construction of a moat and earthen walls. Towns of the established Lan Na kingdoms eventually had imposing brick walls, but it is not clear from the chronicles when the original brick walls of Lamphun, Chiang Mai, Chiang Rai, Fang, Chiang Khong, and Chiang Saen were constructed (FIGS. 1, 2). It is believed that the mud walls at Chiang Saen were stabilized by brick during the reign of King Sam Fang Kaen (1401–1442 A.D.) to fend off attacks by the Burmese and the Ho soldiers and bandits from southern China at the time (Chaisano 1987; Lertrit 2000). In a later discussion of the Chiang Saen wall we discuss new

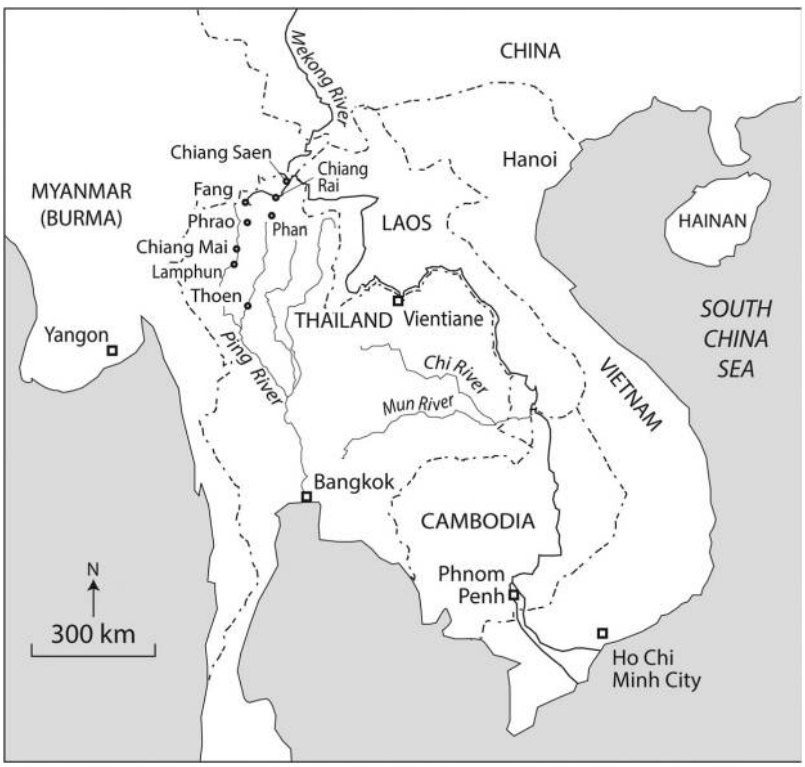

Figure 1 Map of Thailand with locations of rivers and cities discussed in this paper.

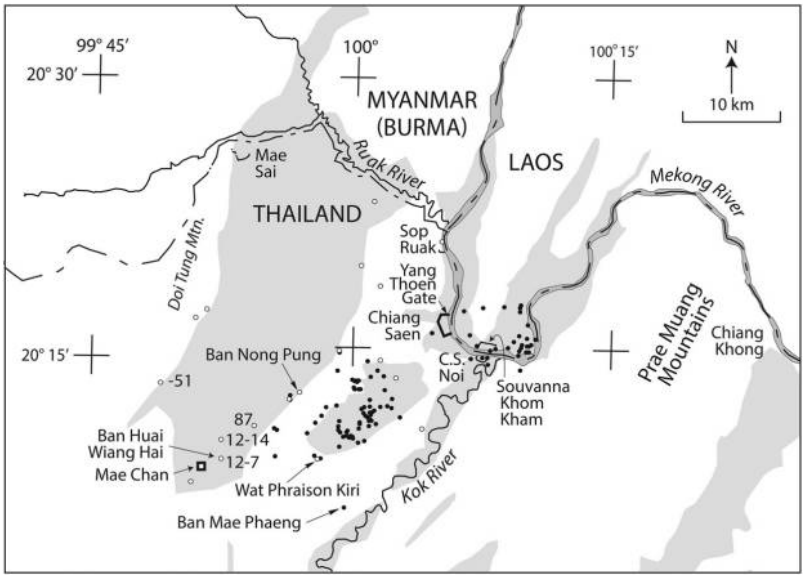

Figure 2 Map showing locations of ruins and earthworks indicative of ancient settlement in the vicinity of Chiang Saen. Solid dots are locations of brick ruins of Lan Na era temples surveyed by students supervised by Narumon Ruangrunsri, Director of the Art and Cultural Center, Chiang Rai Rajabhat University in 2008. Solid circles in Laos are brick and stucco Buddhist monument ruins surveyed by Wood and Wood (2009: slide No. 10). Open circles are of Lan Na towns shown in Shinawatra (2007: 200). Names of modern villages are posted near known earthworks discussed in this report. Shaded areas are lowlands mostly in rice paddy or orchard cultivation. Brick wall and moat surrounding Chian Saen shown by heavy black line. Earthworks at Sop Ruak, Chiang Saen Noi, and Souvannakhomkham shown by a thin gray line.

thermoluminescence ages on brick from the wall. The chronicle states that bricks were made for the Chiang Mai city wall in 1517–1518 A.D. (Wyatt and Wichienkeeo 1998: 110).

Supajanya and Vallibhotama (1972) noted that the encircling earthworks in northern Thailand differ from those of the Mun and Chi River basins (FIG. 1). The earthworks are typically found on small hills, and have irregular shapes guided by the topography. They also noted the lack of potsherds and other artifacts that would have indicated a long period of occupation. They suggested these features were fort towns in which people came to stay in time of war. They emphasized the importance of identifying these features as well as their preservation. Supajanya and Vallibhotama listed earthworks at Phrao, Wieng Manora (near Phrao) and Mae Chi (Phan District) as having two or three ring-shaped plans. Subsequently, Supajanya and Vanasin (1986) inventoried (from air photos) ancient settlement evidence of the Mun and Chi River basins. A map from a report by Thiva Supajanya (n.d.) of the Ruak, Kum, and Mae Chaen River basins, quoted by Shinawatra (2007), shows a number of locations of ancient settlements (FIG. 2).

A photograph of the Phrao trench system appears in the 2004 edition of "A Brief History of Lan Na", in which Hans Penth called it an "old type of Thai Yuan settlement: the former city (*wiang*) of Phrao with triple earth rampart." The system consisted of two compartments, interconnected by two parallel earth walls, and was probably constructed around 1300–1350 A.D. The site is located on a hill called "San Wiang", but it is presently uninhabited, except for the *Wat Jao Lan Thong* constructed in 1935 A.D. (Penth 1972). "*Wat*" means temple in Thai language. The term "*Thai Yuan*" refers to the Thai-speaking people who came from the Yunnan region and settled into this area many centuries before the La Na Period (Ongsakul 2005: 21). In addition, an earthen-moat-and-wall structure 4 m high at Thoen is described by Jumsai (1970). Other ancient settlements are briefly described by Ongsakul (2005).

Methods

From 2010 to 2012 we examined the sites in the field and surveyed elevation profiles across 9 of the earthwork entrenchments (FIGS. 3–9) (TABLE 1). Many of the earthworks were originally identified using 1986 stereo air-photos. Now these features are easily seen through Google Earth. Besides the enigmatic earthworks on hills, we also profiled the degraded city wall and moat of Chiang Saen, prior to its current reconstruction. The earthworks at Chiang Saen Noi and Sop Ruak surround known Lan Na towns containing brick Buddhist monastery and temple ruins from the 13–16th century A.D. We also examined and profiled the rectangular earthwork across the river in Laos which contains similar brick ruins in its interior. Enlarged 1:50,000 scale Thai topographic maps were used in combination with field plotting of features by their UTM (universal transverse mercator)

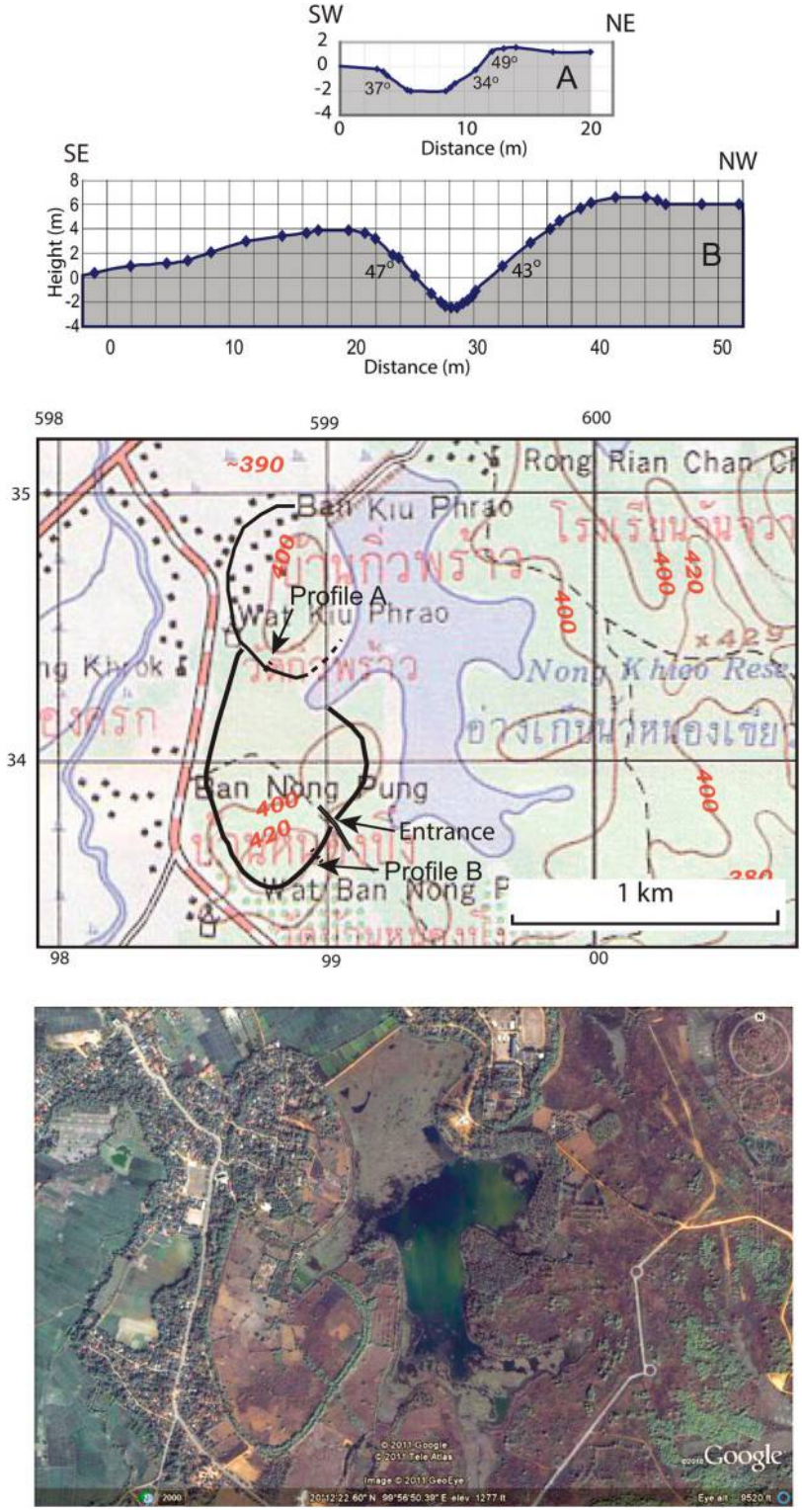

Figure 3 Map and Google Earth image of earthwork trench system at Ban Nong Pung, 11.2 km east of Mae Chan, showing the locations of where elevation profiles A and B were surveyed. The solid line is the trace of the trench, whereas the dotted line is a trace of related earthworks not yet surveyed or profiled. Note that the trench crosses the hill with relief of ~ 25 m just north of Wat Ban Nong Pung. Topographic contour interval is 20 m, with elevations and UTM 1-km grid coordinates (India-Thailand Datum) labeled.

coordinates obtained with handheld Garmin Vista HCX GPS receivers. Older topographic maps use the India-Thailand UTM Grid, while newer maps use the WGS-84 UTM grid (identified in our figure captions). In many cases the outline of the entrenchments on the images can be traced directly onto the topographic map from the Google image using roads and streams for referencing.

Our examination on foot noted the presence or absence of potsherds or bricks within or just

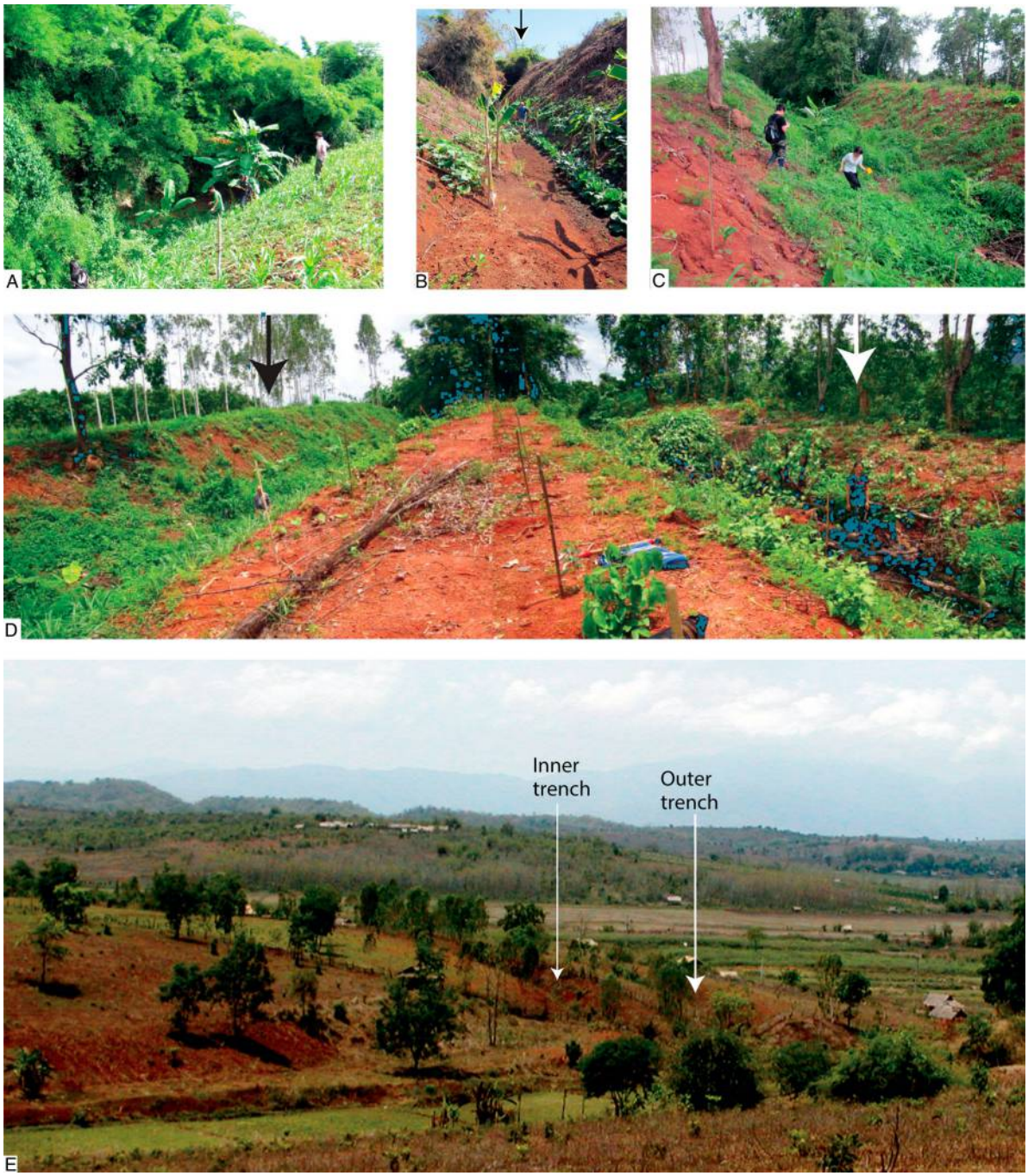

Figure 4 (A) and (B) are photographs of the walls of the earthwork at Ban Nong Pung; C) photograph of the walls of earthworks at Phrao; D) photograph looking south and showing the wall between the double trench at Phrao. The arrow points to people standing in the trenches. The foreground had been slightly graded for a mango orchard. Profile A (FIG. 5) was surveyed in the undisturbed distant area of trees to the south (Photograph by Tan Shumin and Amber Lin Yew Chan); E) Photograph of the NE part of the earthworks near Wat Phraisan Kiri, showing the curved double trench system. Photograph taken looking north from a point 200 m southeast of Profile B (FIG. 7).

outside the encircling earthworks. The surface of the area enclosed or just outside of most earthworks surveyed has been recently ploughed and cultivated. Our survey for bricks and potsherds of the interior areas consisted of 3 or 4 traverses across the breadth of the interior looking at barren ploughed ground or cuts into the soil profile. We only noted the presence of sherds, or their total absence, and did not systematically count number of sherds per area because they were so rare and were undecorated.

Profiling was done using a hand-held inexpensive carpenter's slope indicator (±1° precision) and a 2 m bamboo rod, laid upon the slope end to end. Care was taken to avoid profiles where earthworks have been graded or modified by agricultural activity. The trigonometry of slope distance and the angle of each measurement was determined for horizontal distance and elevation change, and then cumulatively summed for horizontal and vertical coordinate points along the profile. For steep slopes

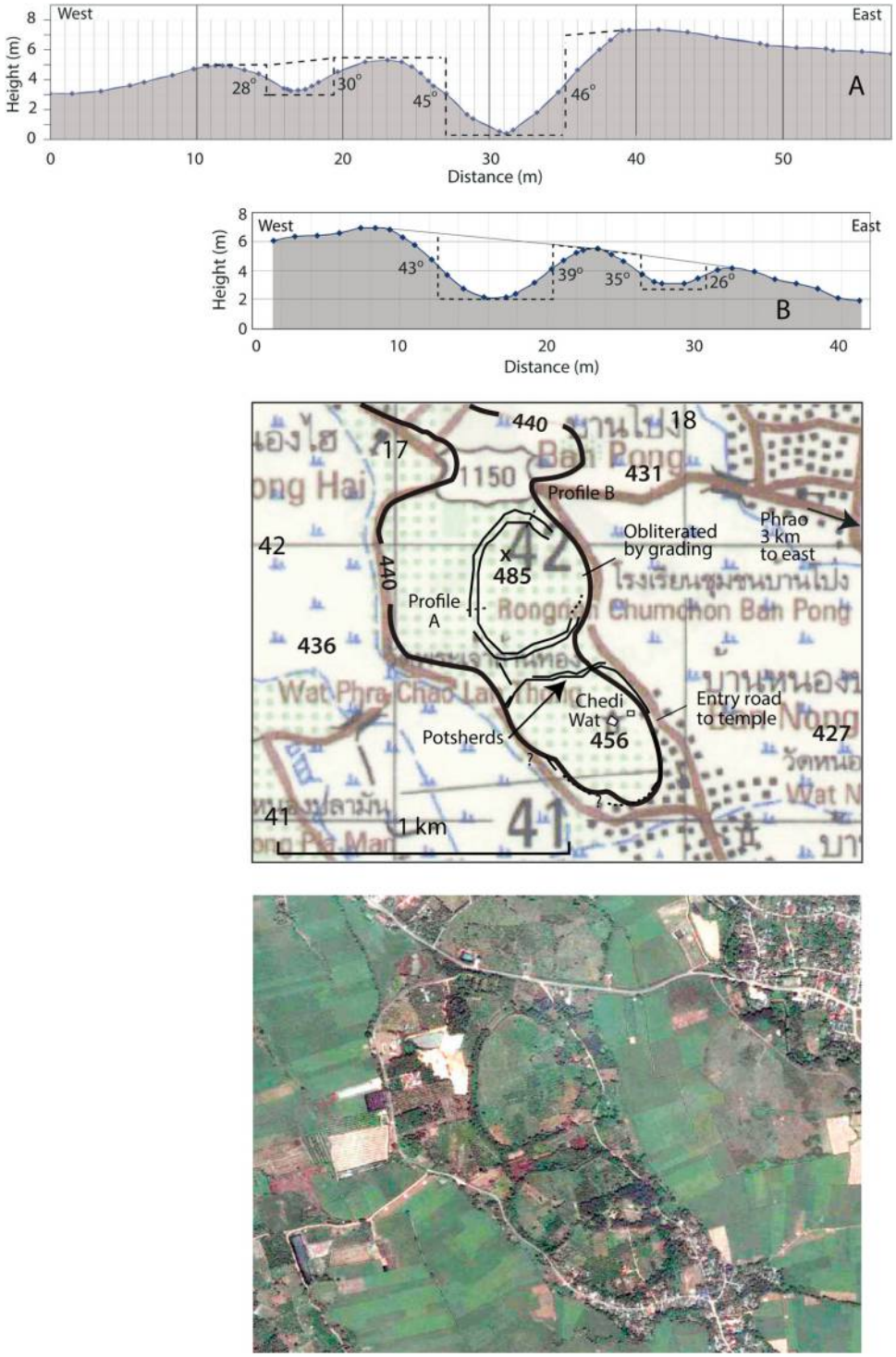

Figure 5 Map, Google Earth image, and profiles of the earthwork trench system 3 km east of Phrao (see figure 1 and table 1 for location of Phrao). Locations of profiles A and B are shown on the map. Dashed line on profiles is the assumed shape of the original vertical-wall construction. Mid-slope angles and UTM 1-km grid coordinates (India-Thailand Datum) are labeled.

(45°), the error of ±1° for the 2-m rod length is ± 2.5 cm. We believe the errors are self-cancelling as the angle is randomly over-read and under-read. The estimated accuracy of distance and height of profiles is ± 0.2 m. This method obtains accurate mid-slope angles that can be used to estimate a relative age based on degradation of the slope since it was originally excavated (Bucknam and Anderson 1979; Nash 1980; Colman and Watson 1983).

To estimate the relative age of the earthworks we applied a diffusion-based approach that takes into consideration the degradation of walls of the earthworks over time (see Appendix). The principal equation for this calculation is the following (Equation 7 in Appendix):

$$\theta_m = \arctan\left[\left(4\pi k\tau/h^2\right) - \cot^2\theta_0\right]^{-1/2}$$

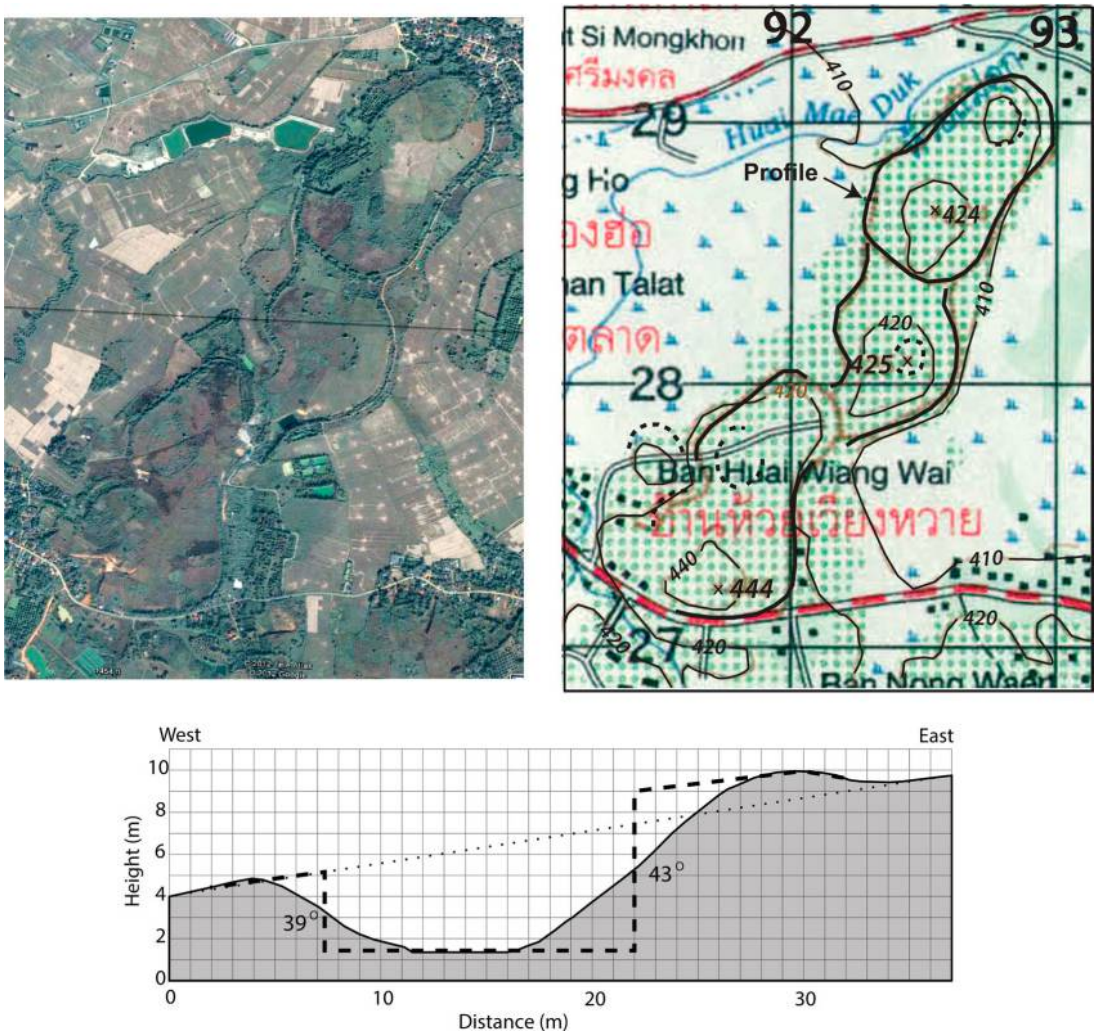

Figure 6 Map and Google Earth image of earthwork trench system at Ban Huai Wiang Wai, 2.2 km east of Mae Chan. Location of the profile shown on the map. Dashed lines are the assumed configuration of the original trench and wall, with UTM 1-km grid coordinates (India-Thailand Datum) labeled.

θ_0 is the initial slope angle of the scarp (assumed to be the angle of repose, or 50° for the study areas (see Appendix); θ_m is the measured mid-slope angle; k is the diffusion coefficient ($m^3\ m^{-1}\ y^{-1}$); τ is the time interval over which the slope angle diminishes as a diffusion process; and h is the height of the scarp or face of the earthwork. The equation produces a set of curves from measurement data that can be used to calibrate k for a feature of known age, and then to infer ages from height-slope data on features with significantly different age. We refer the reader to the Appendix for details.

Descriptions of Earthworks

Earthen trench at Ban Nong Pung

A single earthen trench encircles a 0.31 sq km area on a hill east of Ban Nong Pung ("*Ban*" means village in the Thai language) in Chiang Rai province, 11 km east of Mae Chan (FIGS. 2, 3). The trench intersects a second oval-shaped trench system to the north that encircles a smaller area of the village of Ban Kiu Phrao (FIG. 3). The Ban Kiu Phrao earthwork is clearly a moat, but the Ban Nong Pung trench climbs a hill with relief of 30 meters, and cannot hold water. The Ban Nong Pung trench is 6 m deep and 12 m wide, with an inner trench wall 9 m high (FIG. 4A, B). A roadway cut to the level of the bottom of the trench, passing through the southeast side, appears to have been a gate into the protected area, or a path for elephants. At the northeast side is a low 150 m wide *swale* (small, low lying, wet stretch of land) that is flooded by the Nong Kheo Reservoir, apparently a low and marshy area into which the trench was not extended. A preliminary search of the surrounded hill did not reveal any broken bricks or pottery. It therefore appears that the southern trench did not surround a village. The area within the northern Ban Kiu Phrao trench is a modern village, thus the presence or absence of historical artifacts cannot be easily verified.

The double-trench system near Phrao

Three kilometers west of the town of Phrao in Chiang Mai Province (FIG. 1) are two earthen trench systems

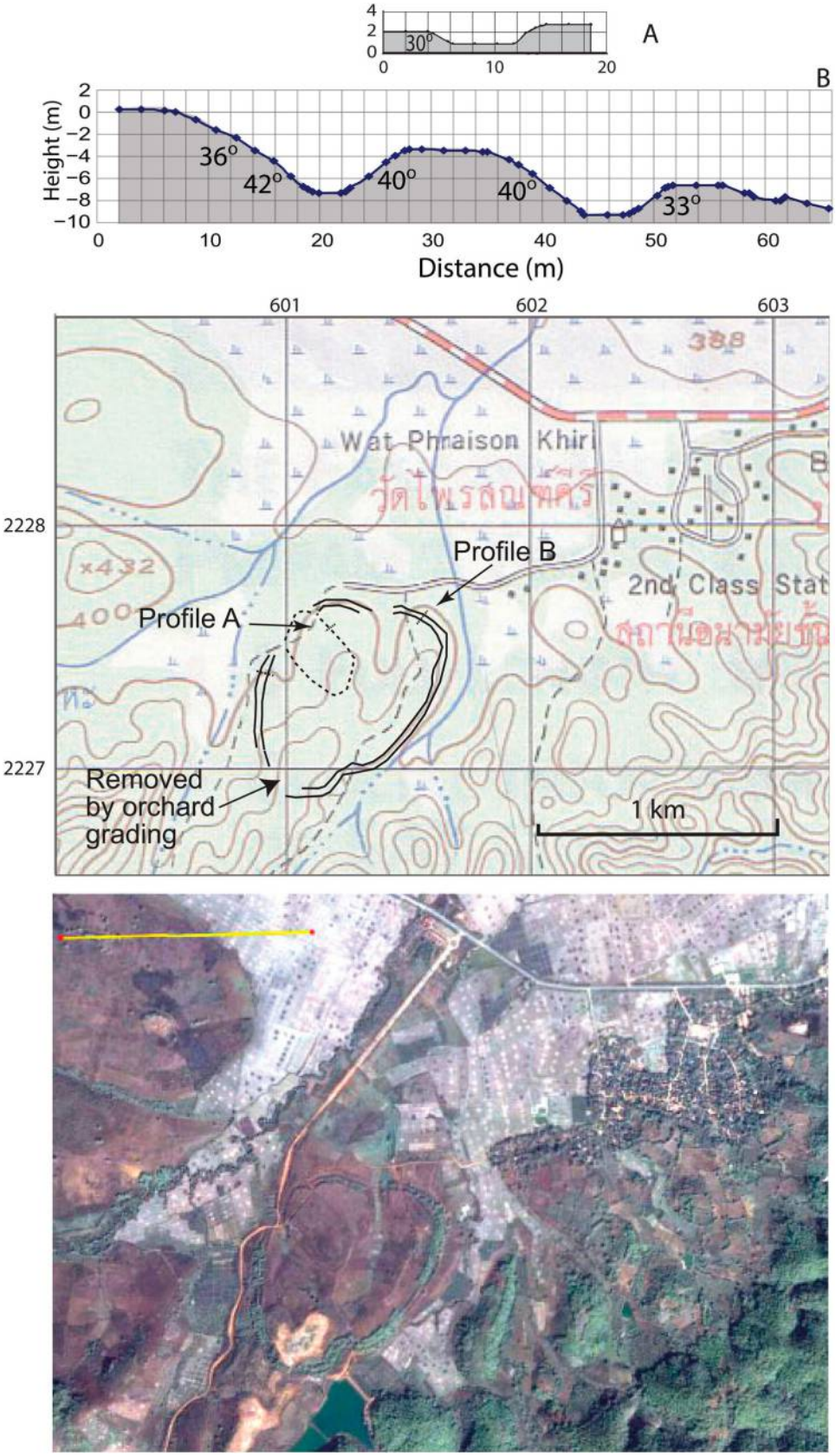

Figure 7 Profiles A and B, map, and Google Earth image of the double-trench earthwork near Wat Phraison Kiri. The map shows its position on a 50-m high hill. Topographic map with 20-m contours and UTM 1-km grid coordinates (India-Thailand Datum) labeled.

that encircle a hill that rises 25 m above the flat valley bottom. The hill is called San Wiang by the local people (Penth 1972, 2004). The northern entrenchment consists of an inner and outer trench and encloses an area of 0.13 sq km (FIG. 5). Assuming the original trenches had vertical walls

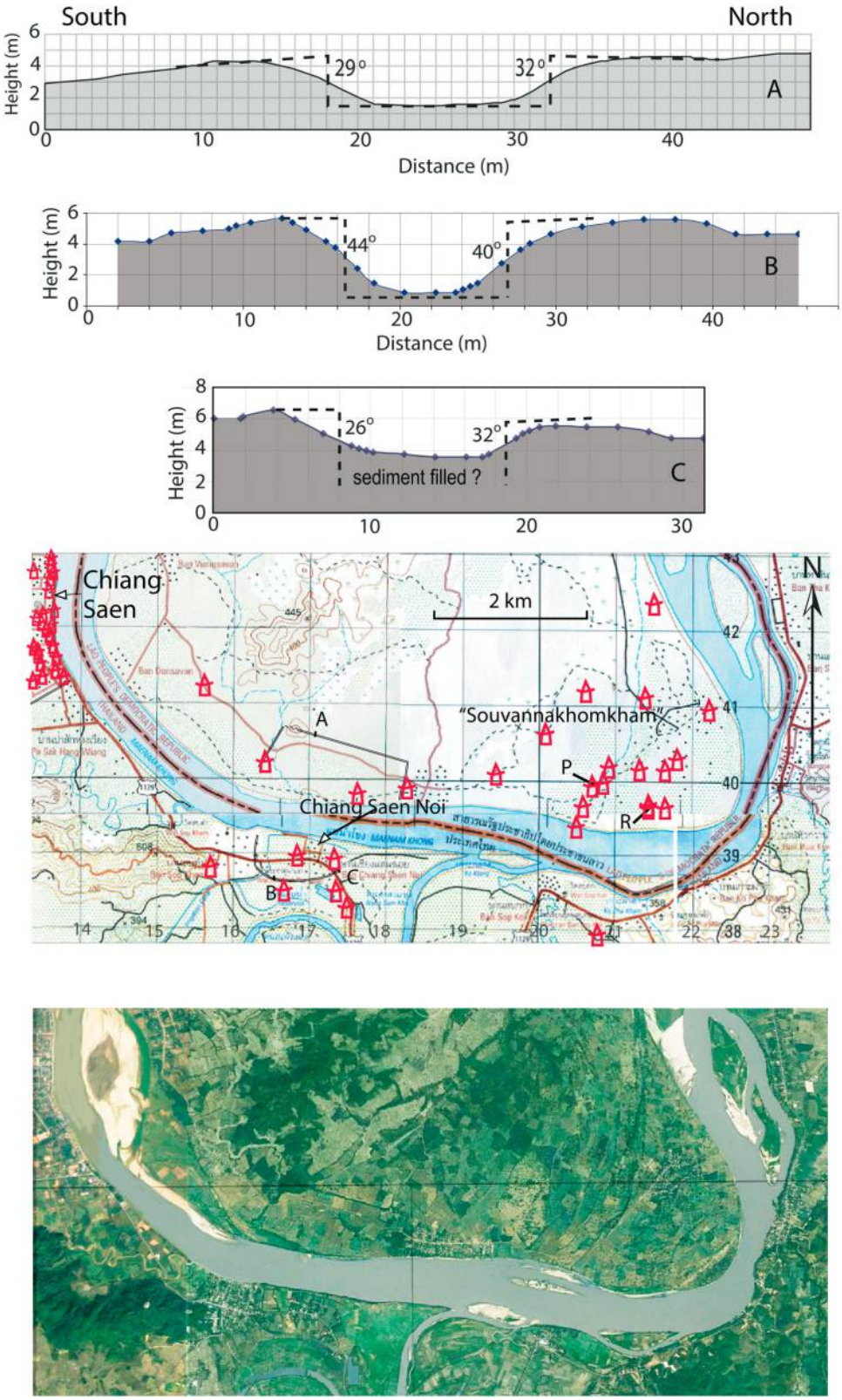

Figure 8 Profile A of rectangular earthwork at Souvannakhomkham (shown also in FIG. 9A), and Profiles B and C at Chiang Saen Noi. Map shows profile locations A, B, and C, and trace of earthworks as a black line. Locations of brick ruins of Buddhist temple sites shown by red symbol. UTM 1-km gridlines (WGS-84 Datum) labeled.

and have eroded to their present slopes of 35 to 43°, the original dimension of the inner trench was 9 m wide and 5 m deep, the outer trench 5.5 m wide and 2 m deep; and the intervening divide was 5 m wide (FIG. 4C, D). It is unclear whether a substantial rammed earthen wall ever existed at this site. Discontinuous mounds 1 m high occur along the inside of the inner trench, but there is no obvious construct of *spoils* (earth and rock excavated or dredged) from the excavation.

Figure 9 A) View looking west and uphill of the trench earthwork at Souvannakhomkham and location of profile A seen in figure 8. Person at left (south side) for scale. Bottom of trench is 10-m wide and the trench is 3-m deep. The photograph shows that the trench runs up a 40-m high hill in the distance and could not have held water; B) ruins of a bell-shaped stupa at location R (FIG. 8); C) ruins of a redented style (stupa-form terminology from Leksukam 2005) stupa at location P (FIG. 8); D) photograph showing the earthen-walled moat and the partially reconstructed brick wall of the city of Chiang Saen. Degraded slopes down to the left are similar to those of most other earthworks in the region.

On the west side of the hill, a single 4 m deep trench, 100 m long, runs to another double-trench system to the south (FIG. 5); however, it does not connect at grade, and does not appear to be for water conveyance. The southern double-trench system is partly obliterated by road grading and a village, but remnant segments show a similar double trench system 3 to 4 m deep. A few potsherds were noted along the northern rim and in the vicinity of Wat Phrao Chao Lan Thong. The sherds are unglazed and have no distinctive shape or decoration. Near the wat (temple) are abundant broken brick and roof-tile debris of an earlier Lan Na age temple. Penth (1972) mistakenly called the earthworks a "triple earthen rampart." Today, the feature that appeared to be the third wall is a divide between two trenches, without any trace of construction (FIGS. 3, 4D).

The Single Trench System at Ban Huai Wiang Hai

Several intersecting ovoid and circular entrenchments encircle hills near Ban Huai Wiang Wai, 2 km east of Mae Chan, Chiang Rai Province (FIGS. 2, 6). The northern, central, and southern enclosures each encircle areas of about 0.3 sq km (TABLE 1). Much of the earthwork system has been modified by agricultural development. However, we were able to survey an elevation profile on the northernmost structure that appeared unaltered. The single trench is 3.5 m deep and the inner wall of the trench is 7.5 m high (FIG. 6): the upper 1.5 m appears to be piled-up spoils. The sloping floor of the trench could not have held water. The area was not fully examined for potsherds, but none were noted.

The Double-Trench System near Wat Phraison Kiri

A double-trench, oval-shaped system encloses a 0.41 sq km area, on a hill, 1 km southwest of Wat Praison Kiri, 12 km east of Mae Chan, Chiang Rai Province (FIGS. 2, 4E, 7). The entrenchment lies upon a hillside with 50 m of relief, and could not have held water as a moat (FIG. 7). The interior was thoroughly searched for indications of a former village, but broken bricks or pottery are nonexistent. We believe this site was never an area of permanent habitation.

The inner trench is 12 m wide, with a 7.5 m high inner wall, assuming that the original walls were excavated vertically. The flat-topped separation ridge between the inner and outer trench is 14 m wide (FIGS. 4E and 7). At the north end of the system is a gap in the double trenches. The gap is a swale with a flat bottom 100 m wide; it is currently a rice paddy. The east side of the swale is a north-south oriented trench. This perpendicularly-oriented and truncating trench is 4 m deep, 10 m wide, and 37 m long, with a 4 m berm ridge on the west side. Though water springs seep into the lower part of this swale, so that the enclosure did have an accessible small water supply, the springs are too low in elevation to fill the trench.

The double-trench system is again interrupted by a smaller entrenchment (shown by a dashed line on FIG. 7). This encirclement encloses a 0.06 sq km area with a trench 5 m wide and 2 m deep (FIG. 7, profile A). The south end of the double-trench system has been partly obliterated by excavation and leveling for a rubber tree plantation, exposing barren bedrock of medium-crystalline black diorite.

Earthen Trench at Souvannakhomkham, Laos

In the Bokeo Province of Laos, across the Mekong River from the ancient Thai town of Chiang Saen Noi, is a rectangular earthwork entrenchment roughly 2 km by 0.5 km, with an open side along the river (FIGS. 2, 8). The earthwork runs up a 40 m high hill at its northwest corner (FIGS. 8, 9A). This section of the earthwork could not have contained water. The trench is 3 m deep in places. The bottom of the trench is 14 m wide (FIG. 9A). Within the enclosed area are the ruins of only two brick Lan Na style monuments, whereas at least 20 sites of brick monuments are located outside the enclosure. The area of concentration of ruined stupas, temples, and Buddha statues (FIG. 9B, C) to the east along the river is called Souvannakhomkham by Lao people. We surveyed locations of these ruins in 2008 when hillsides and fields had been burned and cleared for rainy season planting allowing for an unobstructed view of the trench (FIG. 9A). When this trench was profiled in 2012, the entire area had been converted to banana plantations. Construction of rock groins to prevent riverbank erosion of the plantations had partially destroyed at least one temple site.

Many of the Thai chronicles indicate an ancient city near the mouth of the Kok River. This legendary city, which preceded the founding of Chiang Saen, was named Meuang Suwanakhomkham (Ongsakul 2005; Rattanavong, personal communication 2006; Shinawatra 2007: 41). Little or no archaeological study has been done of this area in Laos. All of the ruins near the mouth of the Kok River, and across the Mekong in Laos, appear to be of Lan Na style. The ruins in Laos may have been an extension, or a part of the La Na cities of Chiang Saen and/or Chiang Saen Noi (Lorrillard 2000) and not those of an earlier city. However, the slopes of this earthwork are the shallowest (29–32°) of those examined in this study, suggesting to us that the trench is older than Lan Na time (discussed below).

Only a part of this earthwork could have held water. Its shape and position among the temple ruins indicate

it was built for defensive purposes. Like the Chiang Saen Noi earthwork, this earthwork at Souvannakhomkham extends to the bank of the Mekong River. The river bank is 10 m high at low water in the dry season. Apparently the offensive invaders were not expected to attack from boats, and if they did, the 5 to 10 m high river bank (during dry season) would have been an effective defensive impediment. Access from boats on the river was most likely as it is today: steps cut into the silt banks. The steps provide a stairway at strategic access points that could be easily defended.

The Entrenchment around Chiang Saen Noi

A half-circle earthen entrenchment about 1 km diameter encloses much of the old site of Chiang Saen Noi (an area of about 0.62 sq km) on the south bank of the Mekong River in Chiang Rai Province (FIGS. 2, 8). Where preserved on its west side, it is 4 to 5 m deep, and 15 m wide (FIG. 8). The east end of the trench has been partially filled with Mekong River flood sediment. A piece of charcoal from sediment found 5 meters deep near the bottom of the infilled trench, exposed in the riverbank, gave an AMS radiocarbon age of CAL A.D. 1475 ± 38 (UGA: 12230) (Wood *et al.* 2008). According to the Jinakalamali Chronicle, the city was founded in A.D. 1327, two years before the city of Chiang Saen (Penth 1994). It is believed to have been a temporary camp site for Phaya Saen Phu, as he was constructing the walled city of Chiang Saen. Temple ruins within the earthwork indicate it was an important village in Lan Na time.

The Entrenchment at Sop Ruak (The Ancient Town of Wiang Chiang Miang)

An arcuate (bow-shaped) moat-like trench is located at the south side of the village of Sop Ruak, in Chiang Rai Province (FIG. 2). The feature runs from the bank of the Mekong River westward 0.6 km to the 100 m long pond that borders the hillside. The pond and rice field to the south are clearly located on an old side channel of the Mekong. They were likely in existence at a time when the area now occupied by Sop Ruak may have been an island. The western part of the trench has been leveled; only the eastern 0.4 km is preserved. The inner wall is 5 m high, the upper meter comprised of a mound, 1 m high (FIG. 10).

Chiang Saen Brick Wall and Earthen Moat

The brick wall and earthen moat of Chiang Saen encloses an area of about 2 sq km (FIG. 2). Within the ancient city are at least 75 brick monuments, mostly Lan Na age stupa and temple foundations in various states of restoration. This moat and wall system was clearly built for defense of the city. The walls were almost certainly maintained by the Burmese military until the time of their defeat in 1804 A.D.

The brick wall encircling Chiang Saen was partly excavated and reconstructed between A.D. 2009 and 2013 (Sivakorn Karn Chang Co., Ltd. 2013). Excavation revealed older earthen walls 3 m high beneath the brick walls. The apparent ages of 13 soil and brick samples from the excavations were determined by Dr. Krit Won-in at the Thermoluminescence Laboratory of Kasetsart University. One brick age was A.D. 327±143 and six soil chunk samples ranged in age from A.D. 327–776. Another brick age was A.D. 974±83 and two soil samples ranged from A.D. 710 to 936. Three brick samples, presumably from the uppermost brickworks, ranged from A.D. 1330 to 1531. We presume the thermoluminescence analysis are on coarse-quartz-grain

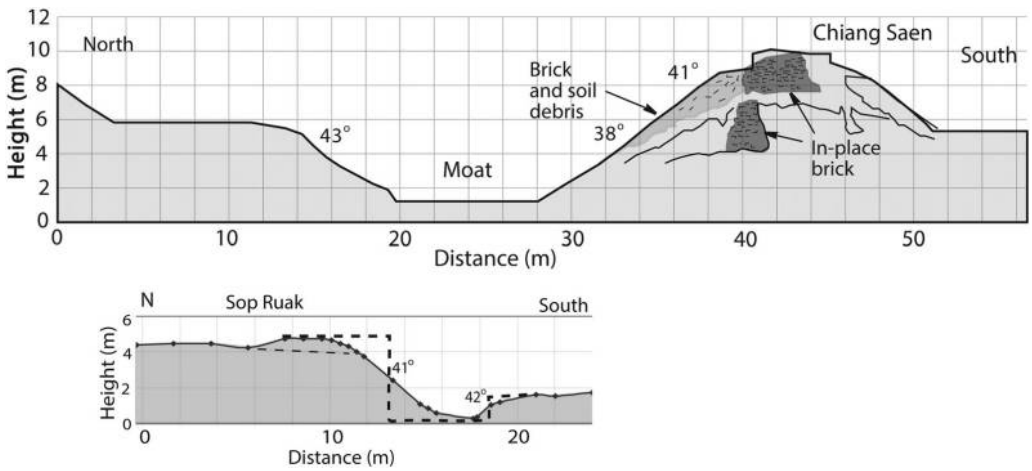

Figure 10 Upper elevation profiles is of the brick city wall and earthen moat of Chiang Saen 50 m east of Yang Thoen Gate (location shown in figure 2). The Thailand Fine Arts Department discovered the intact original brick wall during an excavation of the wall, and posted an information plaque at the site. Much of the inner wall has been reconstructed, but the outer wall and moat appear to have naturally degraded similar to earthworks elsewhere in the region. The lower profile shows the remnant earthen trench south of Sop Ruak (location shown in figure 2).

separates as described by Won-in and colleagues (2008). The report available to us (Sivakorn Karn Chang Co., Ltd. 2013) does not give details on sample processing, consideration of adequate bleaching, or stratigraphy of sample locations. These ages are intriguing because they are the first dated physical evidence to corroborate chronicle legends of a pre-Lan Na city at Chiang Saen, and we await interpretation by Thai colleagues of their significance.

An important pre-La Na city surely existed at this site. The chronicles write that King Mangrai, the founder of the La Na Kingdom descended from a lineage of rulers beginning in A.D. 639, and was born here in A.D. 1238 (Wyatt and Wichienkeeo 1998: 9; Wyatt 2003: 34). The foundation of Chiang Saen as a walled fortress is credited to the reign of his grandson, Saen Phu, in A.D. 1329. Wyatt and Wichienkeeo (1998: 59) have translated from the chronicles: "He had a moat dug around the city on three sides—the moat on the eastern side being the Mekong River—and had walls built on all three sides; and Saen Phu then reigned in that city which has been called Chiang Saen to the present day." The chronicles write that Chiang Saen was built in A.D. 1327/28 and 1329, measuring 1500 fathoms by 700 fathoms (3000 by 1400 m) with five gates (Wyatt and Wichienkeeo 1998).

The moat may have been filled by water from the 2 sq km drainage area of Huai Hom ("*Huai*" means stream in Thai language) via the old oxbow of the Mekong, Nong Bua, or from the much larger Huai Kiang (> 20 sq km drainage area, shown on map of Wood *et al*. 2008: fig. 2). Dry season water from the Mekong or nearby Kham River is 5–10 m lower than the moat. Therefore these streams seem unlikely sources of moat water. Access to water from these streams to fill the moat may have been a factor in the original engineering of the town.

There has clearly been erosion of the Mekong River bank at Chiang Saen, Chiang Saen Noi, and Sop Ruak, and across the river at Souvannakhomkham (Wood and Wood 2009), but there is no evidence that a moat, entrenchment or wall ever existed on the Mekong River sides of these cities.

We surveyed the profile of a segment of the crumbled wall prior to its reconstruction in 2013. The relief from the bottom of the moat to the top of the wall is 8 meters. In a cross section, the vertical outer brick part of the wall appears to be 5 m high (FIG. 10). The moat was 10 m wide and 3 m deep below the wall. It is not known how the sloping walls of the moat were maintained. If water-filled, a vertical slope would not have been stable. The present slope of the inner and outer sides of the moat are 38° and 40°, respectively (FIG. 10). The degraded slope of the crumbled brick wall is 41°. These slopes are similar to the other surveyed earthworks.

Other Earthworks not Surveyed

Much of the rambling entrenchment on the west side of Mae Sai has been filled by development. We surveyed a remnant on the south side, but the result is questionable (TABLE 1). The earthworks at Thoen (Jumsai 1970) were not examined, nor were the many sites mention by Ongsakul (2000) and those on an unpublished map of Thiva Supajanya quoted by Shinawatra (2007). We have seen the Google Earth images of similar earthworks at Si Don Mun, Kok River Valley, and Fang (TABLE 1), but did not visit them.

Purpose of the Earthworks

The examined entrenchments must have originally been constructed with near vertical walls. In this region of Thailand, the cohesive clayey soil mantle of hills can be hand-excavated with a hoe and shovel to depths exceeding 5 meters, down into the saprolite. Furthermore, walls more than 10 m high will stand at a steep angles (>60°) for many years—in part, because of cohesion of the red-clay soil, and also because of the case-hardening by iron oxides of the exposed surface of lateritic soil. For the sites where the material is clayey floodplain silt (described in Wood *et al.* 2008) excavation is easier; and recently cut river banks remain nearly vertical for several years. As the entrenchments have not been used in recent times, the walls have eroded to slope angles of 29° to 47°.

These entrenchments may have had a log stockade to help them be a more effective defensive or containment structure. If for containment, presumably the stockade would have been built along the outside perimeter. If for defense against an invading army with elephants, the stockade would have been built at the top of the inside embankment. When the earthworks fell into disuse, these log structures, if they existed, would have rotted away, or have been carted off for building other structures. We did not excavate but it is possible that excavation might find post-hole evidence of stockades.

Although little is known of life in the region prior to the 13th century, one need only read a few pages of the Chiang Mai Chronicle (Wyatt and Wichienkeeo 1998) to learn that towns of sizeable population and wealth were often attacked by bandits, neighboring rulers and the Chinese Ho invaders, prior to and during Lan Na time. Clearly, many of the earthworks described in this paper were not moats, as they were constructed across hills. Therefore, we hypothesize they were used for the containment of elephants or perhaps had a dual purpose of also providing a

semi-defensible area to which villagers could flee when attacks were anticipated.

The manual effort to construct one of these circular trenches was considerable. The circumferences we surveyed were typically 1.2 to 2 km in length; and the cross-sectional areas were roughly 50–60 sq m. Thus, the excavation of the 1.2 km length double trench at Wat Phraison Kiri involved removing 72,000 cu m with hand tools. If we assume two manual laborers can excavate and remove 3 to 8 cu m per day (Stiedl 1968), a feat of this nature would require 18,000 to 48,000 person days. It would have taken 200 workers several months to complete the earthwork. This seems an attainable effort for an army to trap/contain elephants or for a defensive structure. Likely some or all of the work was done by corvèe or captive labor.

Warfare in Asia involved elephants until the late 19th Century (Nossov 2008: 32). Entrenchments, stockades, and moats would have been constructed to deter attacks with elephants. Certainly a 3-m high vertical earthen wall would impede an elephant, and could only be surmounted by foot soldiers with a ladder. Sukamar (2003: 365) indicates a trench 2 m deep, 2 m across the top, and 1.5 m across the bottom would be sufficient to contain or prevent elephants from crossing into agricultural areas. If used for defense, we recognize that some double-trench earthworks are designed poorly. For example, soldiers standing at the top of the inner trenches of double trench systems had limited view of the outer trench. Thus, they could not fire arrows [or gunfire at later times] at attackers who sought refuge in the outer trench.

The most puzzling entrenchments are those that do not encircle areas with potsherds and brick debris of pre-existing villages. It is quite possible that these were constructed to capture and contain elephants, regardless of their potential for military defense. Vikram Nanjappa (personal communication 2001) writes that the capturing of elephants in pens or stockades is a widely known method known as *Khedda*. This word is derived from the Hindi word *khedna*, which in turn is derived from the Sanskrit *khet*, which means to drive. Elephants were literally driven into pens or stockades. Nanjappa further writes:

> The original method as practiced in Northern India by the people loosely termed 'Aryan' was a simple large space enclosed by a circular trench. The trench was usually thirty feet wide and twenty four feet deep. The excavated soil was thrown up into a steep bank on the outside. The only entrance was a bridge covered with a deep layer of earth, turf and leaves strong enough to take the weight of elephants. Female decoy elephants were kept in the enclosure. Men kept a watch from hiding places in the bank of earth and once a wild herd entered the enclosure they would demolish the bridge thus effectively trapping the herd. The trapped herd would be kept without food and water and after a while the bridge would be rebuilt and domesticated elephants introduced to subdue the wild herd. This method of capturing elephants evolved over time. For example, walls were added; trenches may have been added for reinforcement; bridges were replaced by gates; and wild elephants were driven in instead of being lured by decoys.

Interpretation of some of the earthworks as "elephant corrals" explains their association with nearby villages, and the absence of temple ruins or pottery sherds within the enclosure.

Age of the Earthwork Excavations

From historical accounts, the Lan Na time (~455 to 720 years ago) is the most likely time when these earthworks were built. Earlier towns surely existed in northern Thailand, but no sites have been confirmed other than the Dvaravati towns near Lamphun. Furthermore, favorable town sites would have been rebuilt during Lan Na time, and many earlier earthworks modified. The earthworks were likely maintained during times of hostilities; and we cannot be certain that they were left to decay during Burmese occupation. Because hostilities generally stopped in A.D. 1804, there was no need to maintain the earthworks, unless they were used for other purposes, such as elephant containment.

To test our hypothesis that the earthworks were abandoned 400–500 years ago, we employed Equation 1 and the methods outlined in the appendix to generate several curves for various values of $k\tau$ and θ_0. The curve of this equation that best fits most of the data points is the heavy solid line of figure 11 for which $k\tau = 0.79\ m^2$; $\theta_0 = 50°$. We do not perform a rigorous error analysis of curve fitting, but inspection of figure 11 shows that curves for $\theta_0 = 50°$, and $k\tau$ values between 0.5 and 1.0 m^2 contain most of the data, and error on $k\tau$ is about $\pm$ 0.25 m^2. If we assume most of the entrenchments were maintained up to the time of Burmese occupation 455 years ago, and that the initial collapse of the walls occurred over 55 years, our estimated value for k is 0.0020 $m^2\ y^{-1}$ (calculated as $k = 0.79\ m^2$ / 400 years, as discussed in the Appendix). From discussion above of the possible error in $k\tau$ values, the associated error in k is $\pm$ 0.0006 $m^2\ y^{-1}$. With this calibration of the k value we produce a different curve (FIG. 11) that passes through the points for Souvannakhomkham ($k\tau = 1.99\ m^2$, $\theta_0 = 50°$), and we get a value of 995 years for τ. Given the uncertainty in the estimate of

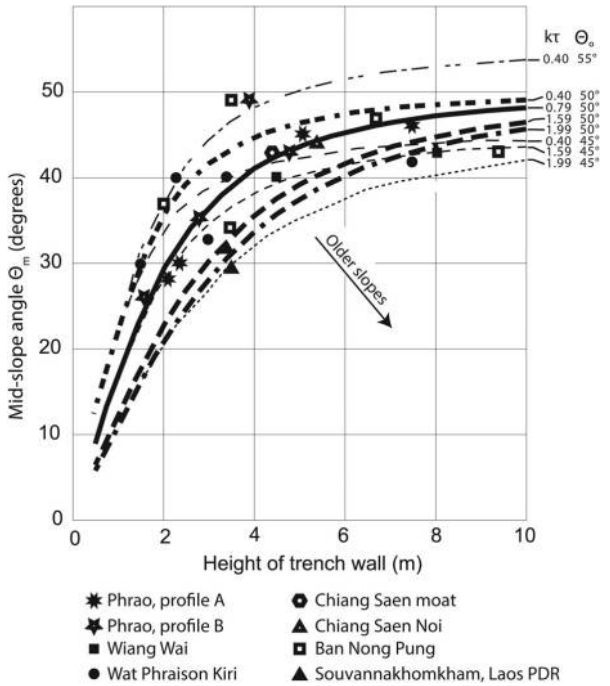

Figure 11 Plot of earthen wall height (h) vs. maximum slope angle θ_m. Various curves use different values of θ_0 and $k\tau$, with the heavy line showing the best fit of the data for $\theta_0 = 50°$, and $k\tau = 0.796$, according to Equation 5 in the appendix.

k discussed above, the age likely falls in the period A.D. 600–1250, which is realistic for the earlier, abandoned, defensive entrenchment built in Laos across the Mekong River from the city of Chiang Saen.

Conclusions

The several earthworks we survey in northern Thailand and Laos are preserved with remarkably steep slopes (29–47°). Similarity of slopes indicate that they were likely constructed in a common time period; and they likely were maintained during the Lan Na time (A.D. 1296–1558). Only the slopes of the 3 m high entrenchment around Souvannakhomkham have distinctly lower sloping sides, 29–32°, suggesting an age of A.D. 600–1250. The complicated and intersecting ovoid map patterns of entrenchments are not easily explained, except that some sections along the trenches could have captured and conveyed water, but could not have held water for a moat. If for defense during a village siege, or if for an elephant corral, the enclosure likely had a water supply. No inner reservoirs are observed, but some have perennial springs (Wat Phraisan Kuri) or are partly bounded by a low wet area or wet rice fields (e.g., sites at Phrao, Ban Huai Wiang Wai, Ban Nong Pung) (FIGS. 1, 2).

The purpose of the double trench is uncertain. A >2 m trench is deep enough to be a barrier to contain or prevent the advance of elephants (Sukamar 2003: 365). The inner small encirclement approximately 2 m deep at Wat Phraison Kiri, may have been for culling elephants. Only at one of these double and single trench systems did we find bricks or pottery shards indicating an abandoned village. Clearly the rectangular earthwork of Souvannakhomkham, and the half-circle at Chiang Saen Noi, encircle a previously inhabited area. The entrenchments combined with the steep river banks, must have been built for defense against invaders and perhaps wild animals (e.g., tigers, rhinoceros, elephants). Similarly the rambling trench outline of Mae Sai (now mostly filled and leveled for modern development) was likely for defense.

We hope our examination of slope-degradation ages may be useful for archaeologists and geologists as other earthworks and scarps are examined in Southeast Asia, and where the slope geometry suggests significant age differences. This study establishes the location of these features in hope that they will be preserved as sites of interest to tourism and archaeological heritage. These ancient sites will be lost forever if they are graded for agricultural or other economic developments.

Appendix: Technical Review

Slope Mechanics and Time

Diffusion Model for Slope Degradation

In this work we make the assumption that these earthworks were originally excavated with vertical or near-vertical walls, assuming their purpose was for defense or elephant containment. We draw from the body of literature that has been published on the degradation of steep scarps formed by earthquakes in our dating of the age of the scarp formation (Nash 1980; Colman and Watson 1983). This application has been extended to investigations of stream and wave cut banks (Hanks *et al.* 1984; Pierce and Colman 1986) and to archaeological earthworks and stone walls (O'neal *et al.* 2005; Pelletier 2008: 45).

An unmaintained, steep-walled earthwork will crumble and erode to a shallow slope over time. The process of slope degradation first involves rain-splash erosion, raveling, slumping and crumbling of the material of the wall accompanied by falling and sedimentation of these materials at the base of the wall. Once the "free face" has been eliminated, a smooth arcuate-upward slope evolves. Slope degradation can then be modeled as a diffusion process (FIG. 12) (Equation 1). The time for this initial "mass-wasting" is uncertain, but estimates are 10 to 1000 years (Kogan and Bendick 2011). Important to the diffusion equation modeling of age is the time (τ_0; years) required for the removal of the free face, and the initial mid-slope angle (θ_0; degrees) at that time, which is commonly assumed to be the "angle of repose."

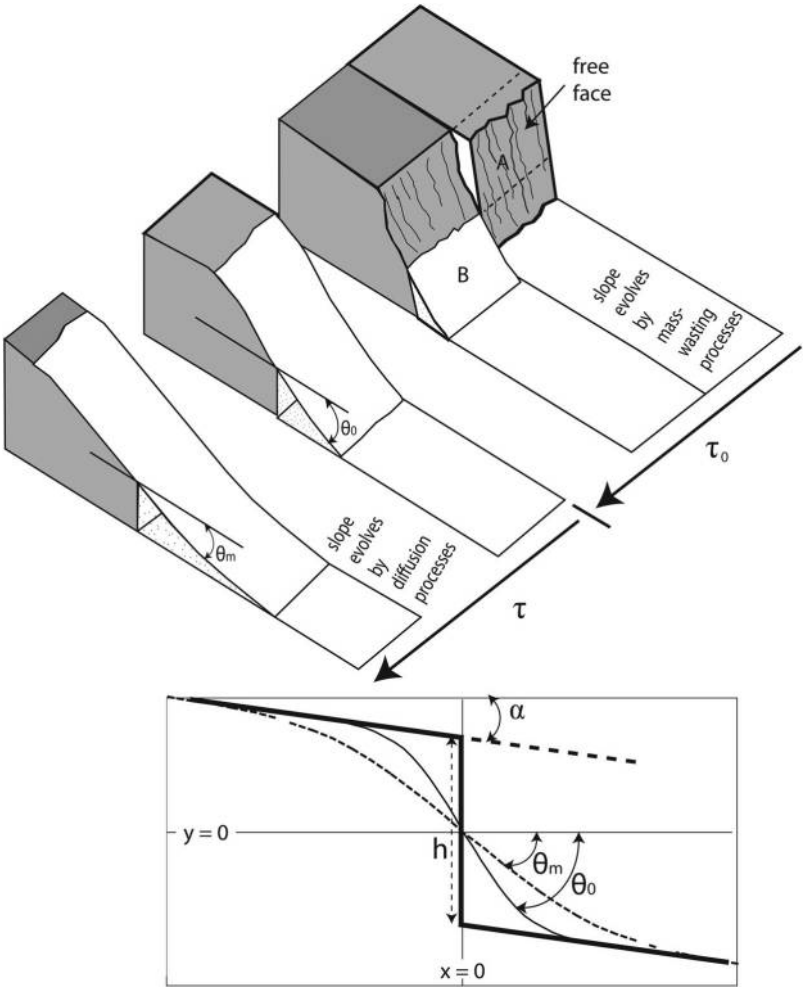

Figure 12 Diagram showing parameters used in the model for slope degradation over time. Note that the vertical coordinate "y" in this figure and in Equation 3, is the same as the vertical coordinate "z" in Equations 1 and 2.

A key assumption for modeling this process as a diffusive process is that the volume rate of downslope soil transport per unit distance laterally along the slope (R; $m^3\ m^{-1}\ y^{-1}$) is proportional to the local slope, $\frac{\partial z}{\partial x}$ (Equation 1):

$$R = k \times \frac{\partial z}{\partial x}$$

k is the diffusion coefficient ($m^3\ m^{-1}\ y^{-1}$), which depends upon the erodability of the soil, the frequency and intensity of slope erosion and slope wash events, and soil creep processes.

A second requirement in modeling this diffusion process is consideration of the continuity equation, which requires that the rate of change in height (z; meters) at any given point is equal to the incremental change in the rate of downslope transport, over an incremental downslope distance x (meters) (Equation 2):

$$\frac{\partial z}{\partial t} = \frac{\delta R}{\delta x}$$

Depending upon initial conditions, solutions involving these equations can involve complicated mathematics (Hanks and Andrews 1989). The following simple solution, which exists for an initially vertical face of height h (meters), imposed on a slope of angle α (degrees) that evolves over time (τ, years), can be used to illustrate the evolution of a slope by linear diffusive processes (Equation 3):

$$y(x, \tau) = \frac{h}{2} erf\left(\frac{x}{(k\tau)^{1/2}}\right) + \tan \propto$$

where x and k are as defined above in Equations 1 and 2, the symbol y is the vertical component and is the same parameter as "z" in Equations 1 and 2. (The symbol "y" should not be confused with unit for reciprocal years which is y^{-1}); and *erf* is the error function, or the Gauss error function, a non-elementary function of sigmoid shape that occurs in probability, statistics and partial differential equations.

However, it is known that the early evolution of the slope is more complicated than the process represented by Equation 3. Most diffusion models therefore start with an assumed slope angle θ_0 (again, near the

angle of repose) that has developed by collapse of the free face over some elapsed time, τ_0 (years). Although Hanks and Andrews (1989) give a solution to the condition of slope evolution with a starting slope angle θ_0, the equation does not lend itself to simple calculations. If one considers only the evolution of the mid-slope angle (θ_m) over time (See the mid-slope point where $x = 0$ on Equation 1), the equation for time reduces to (Colman and Watson 1983) (Equation 4):

$$\tau = \left(h^2/4\pi k\right)\left(1/(\tan\theta_m - - \tan\alpha)\right)$$

where x, τ, h, k, α, θ_m, and θ_0 are all defined as above and shown in figure 12. In the equation, total time is recast into two time periods: 1) the period (represented by τ_0) when the free face of the scarp collapses to an angle of repose; and 2) the time interval (represented by τ) over which θ_m diminishes via diffusive processes. Solving Equation 4 algebraically, and setting $\alpha = 0$ (nearly horizontal "far-field slope") gives the following equation for θ_m (Equation 5):

$$\theta_m = \arctan\left[\left(4\pi k\tau/h^2\right) - \cot^2\theta_0\right)]^{-1/2}$$

Anderson and Bucknam (1979) showed that the easiest measurement is that of the mid-slope angle (θ_m) and the height (h) of the scarp. If one plots these measurements for a group of degraded slopes on a θ_m vs h graph, scarps having the same age τ and the same slope diffusion constant k should follow a curve of Equation 5. Several curves for selected values of kτ and θ_0 are shown in figure 11. The data points (h, θ_m) generally follow the arcuate shape of these curves. High values that lie above these curves may be slopes steepened by recent excavation for road access to cultivated areas.

It is usually assumed that the diffusion constant k is the same for similar materials in a region. If groups of values follow different curves on the θ_m-versus-h graph, they should be of different age. Pierce and Colman (1986) show that the linear diffusion equation and the associated constant k have inaccuracies, and that high scarps degrade faster than predicted. Again, the value of k is dependent on many processes that are not easily quantified. Nevertheless, the concept of diffusive processes diminishing the slope angle is a useful way to estimate age differences of degraded slopes.

For example, each curve in figure 11 has characteristic values of kτ, and θ_0. A curve with $k\tau = 0.79\ m^2$ and $\theta_0 = 50°$ provides a good fit for most of the data. Points lying below this curve are in principal older (i.e., kτ is greater), or the initial slope is less (i.e., θ_0 is $< 50°$). In other words, points below this curve are slopes that are more degraded than the others (i.e., those that fit the curve).

Application to the earthworks in Thailand

We have no data to estimate time, except that all but a few of the slopes measured in this study are smooth curves at an angle shallower than the angle of repose for loose material (~45°). In local road cuts 5 m high, debris typically accumulates halfway up the cut to an angle of 55°, just below marks of the excavator. Published values for failure angles of stiff and firm clay are 56 to 63°. We therefore believe our observed value of 55° is a reasonable estimate of the angle of repose for these deep clay-rich cohesive soils in northern Thailand, rather than a value ≤ 45° reported for cohesionless soils, such as those affected by manual tillage in Thailand and Vietnam (Ziegler and Sutherland 2009; Ziegler *et al.* 2007).

A complication observed in recent northern Thailand road cuts, is that the free face commonly exhibits an iron-oxide encrustation that preserves excavator marks for many decades thus preserving the free face more so than in soils in temperate climates. However, this is a region of high monsoonal rainfall (~1500–1900mm y^{-1}), subtropical temperatures (mean annual temperature of 25.5° C, and very warm afternoon temperatures of 31 to 36° C in the hot dry season extending from February–May, and dense vegetation. Therefore these cuts are frequently exposed to driving intense rain, extreme drying, as well as tree-throw and soil churning—so that the rates of slope evolution may not compare to the many studies done on gravelly soils of temperate and cold climates. Thus, the diffusion constant k is not well known over the various surficial materials and climates of the earth, including Thailand.

In order to appreciate the meaning of k, consider the transfer of a volume of material (FIG. 12) from the upper slope (A), to the lower slope (B) over a period of time. Further, the volume of transfer is only a function of time. The average rate of transfer from the upper slope to the lower slope will have the units $m^3\ y^{-1}$. As we are casting this equation as a two-dimensional view, using x and y coordinates, we are actually considering a one-meter length along the slope in the 3rd dimension, producing units $m^3\ m^{-1}\ y^{-1}$. A simple evaluation of k is the linear average of volume transport over time.

A two-dimensional profile visualizes how much material must have been transferred from the upper part of a vertical cut to the lower part to produce a profile that is observed today. For example in figure 5 (profile A), the 7 m high bank has a midslope angle of 46°. The triangular volume of material removed from a vertical bank and transferred by erosion to the slope below (shown by dotted line) is $7.2\ m^3\ m^{-1}\ y^{-1}$. If the vertical wall has been degrading for 400 years to the present slope, the average rate of

transfer is 7.2 m^3 m^{-1} over 400 years, which is equivalent to 0.018 m^3 m^{-1} y^{-1}. If we consider only the volume that has built up over an early-formed 50° slope (θ_0), the rate is 0.95 m^3 m^{-1} over 400 years or 0.0024 m^3 m^{-1} y^{-1}. While this value has the same units and is similar to k in the diffusion equation model, it does not take into account the height of the scarp, nor the idea that the transport rate is proportional to the slope (Equation 1). We use the best-fit curve for most points from the diffusion equation model (Equation 5), to derive a value for $k\tau$ = 0.79 m^2, and for 400 years, we derive a value for k = 0.002 m^3 m^{-1} y^{-1} (FIG. 11).

Avouac (1993) provides diffusion-coefficient values derived from scarps for semi-arid temperate climates ranging from 0.0003 to 0.005 m^3 m^{-1} y^{-1} (reported as m^2/year). Thus, the value we obtain is within the known range for slope diffusion coefficients, but point out that the value of k we obtain is for cohesive clayey floodplain and lateritic soil in a sub-tropical environment.

Regardless of the uncertainty in estimating k, one can characterize degraded slopes in terms of $k\tau$ and an assumed value of θ_0 simply to compare relative age difference. The lack of variability with respect the computed curves of figure 11 suggests little differences in age; and we believe most are ~450 years old, except for the older entrenchment at Souvannakhomkham, Laos, estimated to have been excavated at some time between A.D. 600-1250.

Acknowledgments

We thank many people for discussions and help in locating and surveying the earthworks: John Roberts of Sop Ruak, Ian and Wassana Smith of Chiang Saen, Kapkeo Xayavouthy of Houay Xai, Laos, and Singapore students: Amber Lin Yew Chan, Tan Shumin, Serene Ng, Ng Chee Kian, Rebecca Neo, Wong Jiayi (Felicia). Kraisin Unchaijin and Saiklang Jindasu (Chiang Mai National Museum) provided helpful discussions and publications from the Fine Arts Department. We appreciate helpful comments from Steve Colman and two anonymous reviewers.

Spencer H. Wood (Ph.D. 1975, California Institute of Technology, Pasadena) is Emeritus Professor of Geosciences at Boise State University. He has conducted fieldwork in the western U.S., and Thailand with interests in geomorphology, sedimentology, geophysical exploration, volcanology, paleoseismicity, geothermal resources and watershed hydrology.

Layle R. Wood (B.A. 1962, University of Oregon, Eugene) has conducted field work in Thailand on geomorphology and archaeology.

Alan D. Ziegler (Ph.D., 2000, University of Hawaii, Honolulu) is Professor of Geography at the National University of Singapore. He conducts field work in SE Asia on environmental issues, catchment hydrology, and geomorphology. Current work compares environmental effects of traditional swidden agriculture with intensified and plantation cultivation on sloping lands of SE Asia., Other research concerns hydrological process related to infectious diseases and human health in developing countries.

References

Avoac, J. -P. 1993. "Analysis of scarp profiles: evaluation of errors in morphologic dating," *Journal of Geophysical Research* 98: 6745–6754.

Boyd, W. E., R. McGrath, and C. F. W. Higham. 1999a. "The Geoarchaeology of Iron Age "Moated" Sites of the Upper Mae Nam Mun Valley, N.E. Thailand I: Palaeodrainage, Site–Landscape Relationships and the Origins of the "Moats," *Geoarchaeology* 14: 675–716.

Boyd, W. E., R. McGrath, and C. F. W. Higham. 1999b. "The Geoarchaeology of Prehistoric Ditched Sites of the Upper Mae Nam Mun Valley, NE Thailand II: Stratigraphy and Morphological Sections of the Encircling Earthworks," *Bulletin of the Indo-Pacific Prehistory Association* (Melaka Papers, Volume 2) 18: 169–179.

Bucknam, R. C., and R. E. Anderson. 1979. "Estimation of Fault-scarp Ages from a Scarp-height-slope Angle Relationship," *Geology* 7: 11–14.

Chaiseno, B. 1987. *A Study on Archaeological Evidence at the Ancient Town in Ampoe Chiang Saen, Changwat Chiang Rai.* Unpublished M.A. thesis, Department of Archaeology, Silpakorn University, Bangkok.

Colman, S. M., and K. Watson. 1983. "Ages Estimated from a Diffusion Equation Model for Scarp Degradation," *Science* 221: 263–265.

Dega, M. F. 1999. "Circular settlements within eastern Cambodia," *Bulletin of the Indo-Pacific Prehistory Association* 18: 181–190.

Garnier, F. 1885 [1996]. *Further Travels in Laos and Yunnan, The Mekong Exploration Commission Report (1866–1869) Volume 2*. Translated by W. E. J. Tips. Bangkok: White Lotus Press.

Glover, I. 2010. "The Dvaravati Gap – Linking Prehistory and History in Early Thailand," *Bulletin of the Indo-Pacific Prehistory Association* 30: 79–86.

Hanks, T. C., and D. J. Andrews. 1989. "Effects of Far-field Slope on Morphological Dating of Scarplike Landforms," *Journal of Geophysical Research* 94: 565–573.

Hanks, T. C., R. C. Bucknam, K. R. Lajoie, and R. E. Wallace. 1984. "Modification of Wave-cut and Fault-controlled Landforms," *Journal of Geophysical Research* 89: 5771–5790.

Higham, C. F. W. 2002. *Early Cultures of Mainland Southeast Asia*. Bangkok: River Books.

Higham, C., and R. Thosarat. 2012. *Early Thailand: From Prehistory to Sukhothai*. Bangkok: River Books.

Jumsai, S. 1970. *SEEN, Architectural Forms of Northern Siam and Old Siamese Fortifications*: Bangkok: Fine Arts Commission of the Association of Siamese Architects.

Kogan, L., and R. Bendick. 2011. "A Mass Failure Model for the Initial Degradation of Fault Scarps, with Application to the 1959 Scarps at Hebgen Lake, Montana," *Bulletin of the Seismological Society of America* 101: 68–78.

Leksukhum, S. 2005. "The evolution of memorial towers of Siamese temples," in F. McGill and P. Chirapravati, eds., *The Kingdom of Siam: The Art of Central Thailand (1350–1800)*. Chicago: Art Media Resources, 61–79.

le May, R. 1926 [1999]. *An Asian Arcady: Land and Peoples in Northern Siam*. Bangkok: White Lotus Press.

Lertrit, S. 2000. "Cultural Resource Management and Archaeology at Chiang Saen, Northern Thailand," *Journal of Southeast Asian Studies* 31(1): 137–161.

Lorrillard, M. 2000. "Souvanna Khom Kham ou Chiang Saen rive gauche?" *Aséanie* 5: 57–68.

Nash, D. B. 1980. "Morphologic Dating of Degraded Normal Fault Scarps," *Journal of Geology* 88: 353–360.
Nossov, K. 2008. *War Elephants*. Oxford: Osprey Publishing Co.
Notton, C. 1926. *Analles du Siam. Chronique de Sinhanavati*. Paris: Imprimeries Charles-Lavaunzell & Cle.
O'neal, M. A., M. E. O'mansky, and J. A. Macgregor. 2005. "Modeling the Natural Degradation of Earthworks," *Geoarchaeology* 20(7): 739–748.
Ongsakul, S. 2005. *History of Lanna*. Chiang Mai: Silkworm Books.
O'reilly, D. J. W. 2001. "From the Bronze Age to the Iron Age in Thailand: Applying a Heterarchical Approach," *Asian Perspectives* 39: 1–19.
Parry, J. T. 1992. "The Investigative Role of Landsat-TM in the Examination of Pre-and Proto-historic Water Management Sites in Northeast Thailand," *Geocarta International* 4: 5–24.
Pautreau, J. -P., P. Mornais, and T. Doy-Asa. 2003. *BanWang Hai, excavations of an Iron-Age cemetery in northern Thailand*. Chiang Mai, Thailand: Silkworm Books.
Pelletier, J. D. 2008. *Quantitative Modeling of Earth Surface Processes*. Cambridge: Cambridge University Press.
Penth, H. G. 1972. "Old Phrao," *The Journal of the Siam Society* 60: 1–4.
Penth, H. 1994. *The Jinakalamali Index, an Annotated Index to the Thailand Part of Ratanapanna's Chronicle Jinakalamali*. Oxford: The Pali Text Society.
Penth, H. 2004. *A Brief History of Lā Nā, Northern Thailand from Past to Present*. Chiang Mai, Thailand: Silkworm Books.
Pierce, K. L., and S. M. Colman. 1986. "Effect of Height and Orientation (microclimate) on Geomorphic Degradation Rates and Processes, Late-glacial Terrace Scarps in Central Idaho," *Geological Society of American Bulletin* 97: 869–885.
Shinawatra, W. 2007. *The Cultural Landscape Associated with the Old Town of Chiang Saen: the Interpretation and Conservation of a Forgotten Heritage*. Unpublished Ph.D. dissertation, Faculty of Architecture, Silpakorn University. http://www.thapra.lib.su.ac.th/objects/thesis/fulltext/thapra/Weeraphan_Shinawatra_Doctor/Chapter2.pdf
Sivakorn Karn Chang Co., Ltd. 2013. *Reconstruction of the Chiang Saen City wall (2009–2013)* (in Thai). Bangkok: Fine Arts Department of Thailand, Ministry of Culture.
Stiedl, D. 1968. *Productivity norms for Labour-based Construction*. International Labour Organisation, Advisory support, information services and Training, Nairobi, Kenya, http://www.ilo.org/public/english/employment/recon/eiip/download/prod_norms.pdf
Sukumar, R. 2003. *The Living Elephants; Evolutionary Ecology, Behavior, and Conservation*. Oxford: Oxford University Press.
Supajanya, T., and S. Vallibhotama. 1972. "The Need for an Inventory of Ancient sites for Anthropological Research in Northeastern Thailand," *Tonan Ajia Kenkyu (The Southeast Asian Studies)* 10(2): 284–297.
Supajanya, T., and P. Vanasin. 1986. "The Inventory of Ancient Settlements in Thailand on Aerial Photographs," *Journal of the National Research Council, Thailand* 18 (2): 1–38.
Unchaijin, K. 2012. *History of Built Settlements in Lan Na* (in Thai). Bangkok: Fine Arts Department of Thailand, Ministry of Culture.
Won-in, K., P. Wattanadul, P. Dararutana, S. Pongkrapan, I. Takashima, N. Ruangrunsri, F. S. Singharajwarapan, T. Supajanya, and K. Vichapan. 2008. "Preliminary Study of the Age of the Lanna Period by Thermoluminescence Dating: A Case Study from the Wiang Kaen Ancient Site, Chiang Rai, Northern Thailand," in R. I. Kostov, B. Gavdarska and M. Gurova, eds., *Geoarchaeology and Archaeomineralogy, Proceedings of the International Conference*. Sofia: St. Ivan Rilski, 130–133. (http://mgu.bg/geoarchmin/naterials/26Won-in-et-al.pdf)
Wood, S. H., A. D. Ziegler, and T. Bundarnsin, 2008. "Floodplain Sedimentation, Channel Changes and Riverbank Stratigraphy of the Mekong River area, Chiang Saen, Northern Thailand," *Geomorphology* 101: 510–523.
Wood, S. H., and L. E. Wood. 2009. "Mekong riverbank erosion of the 14th Century cities of Chiang Saen Noi, Thailand and Souvannakhomkhanm, Laos, PDR," *Geological Society of America Abstracts with Programs* 41(7): 576.
Wyatt, D. K. 2003. *Thailand, a Short History, 2nd edition*. New Haven: Yale University Press.
Wyatt, D. K., and A. Wichienkeeo. 1998. *The Chiang Mai chronicle*, 2nd edition. Chiang Mai, Thailand: Silkworm Books.
Ziegler, A. D., and R. A. Sutherland. 2009. "Modeling Soil Flux by Manual Tillage as a Non-linear Slope-dependent Process," *Soil Science Society of American Journal* 73 (3): 1012–1019.
Ziegler, A. D., T. W. Giambelluca, R. A. Sutherland, M. A. Nullet, and T. Duc Vien. 2007. "Soil Translocation by Weeding on Swidden Fields in Northern Vietnam," *Soil and Tillage Research* 96: 219–233.